Imaging of Fuel Mixture Fraction Oscillations in a Driven System using Acetone PLIF

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Abstract

Measurements of fuel mixture fraction are made for a jet flame in an acoustic chamber. Acoustic forcing creates a spatially-uniform, temporally-varying pressure field which results in oscillatory behavior in the flame. Forcing is at 22, 27, 32, 37, and 55 Hz. To asses the oscillatory behavior, previous work included chemiluminescence, OH PLIF, nitric oxide PLIF imaging, and fuel mixture fraction measurements by infrared laser absorption. While these results illuminated what was happening to the flame chemistry, they did not provide a complete explanation as to why these things were happening. In this work, the fuel mixture fraction is measured through PLIF of acetone, which is introduced into the fuel stream as a marker. This technique enables a high degree of spatial resolution of fuel/air mixture value. Both non-reacting and reacting cases were measured and comparisons are drawn with the results from the previous work. It is found that structure in the mixture fraction oscillations is a major contributor to the magnitude of the flame oscillations.

Introduction

Combustion instabilities are caused by a coupling between thermo-acoustic and fluid-dynamic conditions present during the combustion processes. Combustion instability is defined here as 'the amplification of acoustic waves' due to the thermo-acoustic coupling between energy release from the combustion process and acoustic waves inside the combustion chamber. The interaction between vortices (mixing), sound (acoustic, or pressure oscillations), and combustion heat release can lead to self-excited oscillations that can cause structural damage. Any unsteadiness in the rate of combustion is a source of sound, generating pressure and velocity fluctuations [2]. Especially, as environmental issues becoming more important, lean premixed combustion schemes are being widely employed, which, while reducing the amount of NOx produced by lowering the flame temperature, have a greater tendency to cause instabilities since the combustion occurs near the lean blow-out limits [3].

A series of theoretical and experimental works [1, 4-6] has been done on this subject in JPC, Caltech. The coupled effects of acoustic forcing with combustion heat release on species concentration was examined by Pun et al. [4,5] with OH-PLIF under atmospheric pressure. In figure 1, the flame region is marked as region (1). Phase resolved imaging revealed phase-dependent response of the combustion process under low frequency (22 ~ 55Hz) acoustic excitations. Since this work is closely related to the current work in that both used the same combustion chamber, burner, and acoustic excitations, it is very interesting and at the same time important to compare the effects of acoustic forcing on the energy release and fuel/air mixing.

Fernandez et al. [6] used an infrared laser technique to measure point-wise fuel/air mixing in terms of 'Unmixedness factor' in the same experimental conditions as in the work by Pun et al. Unfortunately, a direct comparison of Pun's and Fernandez's work is not possible because the technique employed by Fernandez is time-, but not phase-, resolved. Fernandez's did demonstrate that fuel/air mixing within the eductor block is heavily affected by the acoustic excitation.

This effort aims to bridge these two studies by producing mixture fraction data that can be directly compared to both Fernandez's unmixedness results and to Pun's OH PLIF results. This work employs single frequency acoustic forcing at five different frequencies, just as the previous efforts, to examine how the local fuel/air mixing is affected by the imposed acoustic excitation and how this relates to the observed flame behavior. By comparison with earlier work [6], it also becomes possible to understand the evolution of fuel/air mixing.

The phase dependence of the mixing process is evaluated by collecting images at random phase values for each frequency. These images are then sorted by phase, with phase defined as a best-fit sinusoid of the acoustic oscillation (as measured by the pressure transducer).

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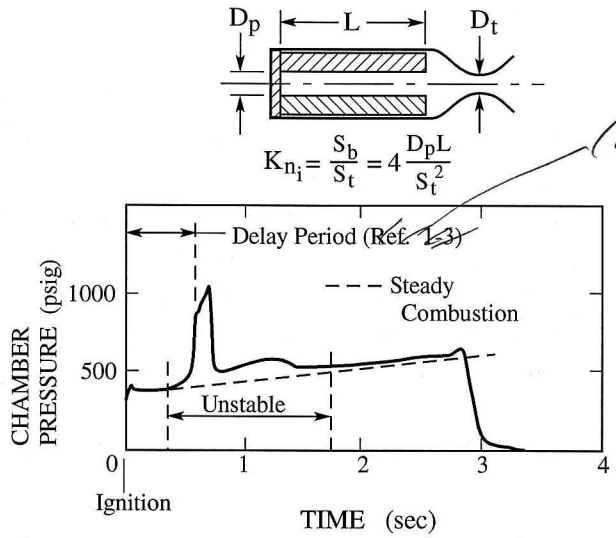

Fuel/air mixture behavior is assumed to vary only with phase and spatial location, which enables averaging of images in each portion of phase (10° degree increments for this study). The phase-averaged images can then be compared to assess phase-dependent behavior. This is similar to the technique employed by Pun in the studies of OH PLIF.

The imaging performed here was planar laser induced fluorescence of acetone. The acetone was employed as a fuel marker to visualize the fuel/air mixing region directly beneath the flame, as illustrated in figure 1. Acetone is seeded into the fuel stream and then imaged to show the distribution of fuel in the flow. This technique enables us to see the 2-D distribution of fuel, and consequently, compute the degree of fuel/air mixing.

Acetone PLIF has been previously studied for various purposes [7-13]. Thurber et al. [7, 8] used this technique to determine temperature. Many of the other studies [8, 9, 11-13] focused on measurement of fuel concentration using the acetone-PLIF where the acetone had been similarly introduced as a fuel marker.. For most of these studies, as in the work by Demayo et al. [12], a single image was taken as a representative of the system, and then the unmixedness was calculated based on this. In effect, the two dimensional image was collapsed to a single unmixedness value. In this paper, 2-D maps of unmixedness factor at each point of the image are calculated, as well as the phase and frequency dependence.

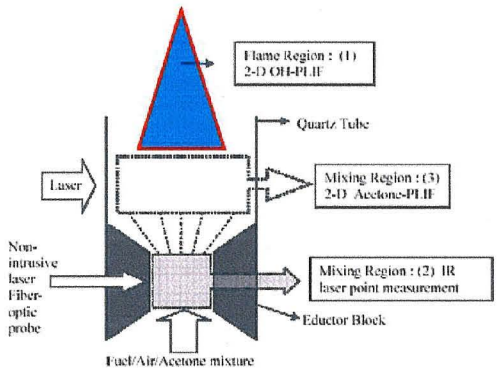

Figure 1. Regions of interest; regions (1) flame region [4, 5] (OH-PLIF), (2) at the neck of the eductor block [6] (Infrared laser), (3) in the mixing region (acetone-PLIF)

Experimental Configuration

Figure 2 shows a schematic of the acoustic chamber and figure 3 illustrates how acetone is seeded into the fuel stream. The chamber exhaust is open to the atmosphere at the top, providing an acoustically open exit condition. A pair of acoustic drivers are sealed to a pair of air jet film cooling rings (to prevent heat failure of the drivers), which are in turn sealed to opposite sides of the steel structure. These acoustic drivers are cooled by air flow. The acoustic drivers are 12 inch diameter sub woofers that can continuously handle 400 W of power. A 1000W power amplifier along with a function generator provides the input signal and power to the acoustic drivers. The acoustic chamber is made of aluminum, with a ring at the bottom, which creates a closed-end acoustic condition. The ring has two sets of inlet louvers cut on opposing sides to allow air to flow into the tube, while maintaining acoustically closed end condition.

The burner (fig 1, 2) is a traditional jet-mixed burner with flame anchoring about in the middle of the quartz tube depending on the fuel/air mixture flow rate. The fuel is 50% methane and 50% nitrogen. The tube is 5.72cm wide on each side and 11.43cm tall. PLIF imaging of acetone, with excitation at 280 nm, is performed at the bottom portion of the quartz tube where no flame is present.

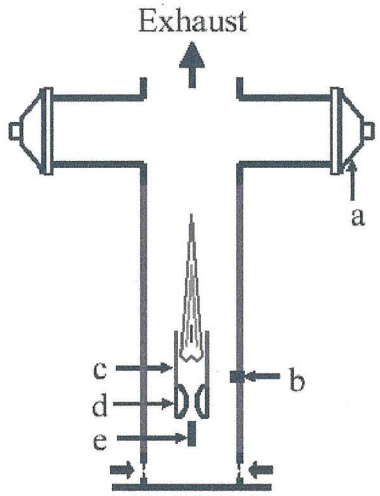

Figure 2. The combustion chamber. (a) : loud speakers, (b) pressure transducer, (c) fused-silica burner tube, (d) eductor block(see fig. 1), (e) fuel spud, arrows at the bottom indicate the air inlet

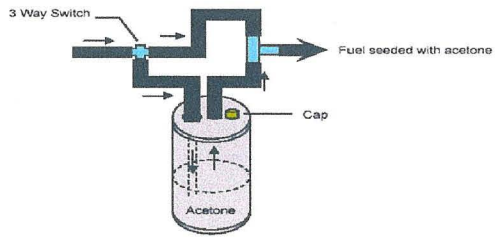

Figure 3. Acetone seeder

Figure 4 is a simplified schematic of the laser and imaging systems. An intensified CCD camera is used for the image acquisition, while a National Instrument data acquisition board (NI PCI 6014) along with pressure transducer (PCB 106B50) is used to measure and record the pressure signal. All timing is linked to the ND:YAG pump laser. The ND:YAG outputs a high power laser beam at 532 nm which then drives a dye laser. The dye laser produces a 560 nm beam which, in turn, is frequency doubled to 280 nm for excitation of acetone. Lenses elongate the height and narrow the width (where the minimum sheet waist is at the image center).

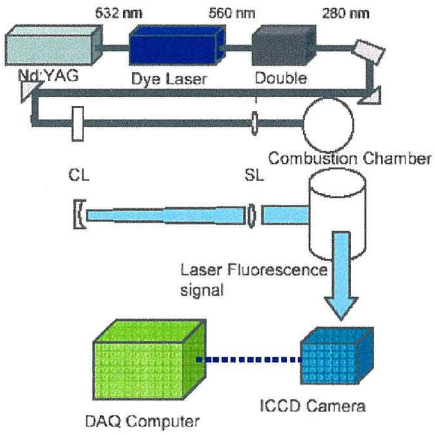

Figure 4. Laser and imaging system configuration

The PLIF signal is captured by an intensified CCD camera with a maximum resolution of 512 by 512 pixels. An area of 5.5 by 4.1 cm is imaged with 160 by 160 microns corresponding to each camera pixel (344 by 256 pixels). The PLIF signal goes through a UV high-pass filter which filters out the scatters from the 300 nm excitation beam. Fluorescence occurs between 350 and 550 nm in wavelength.

Results

For experiments with acoustic forcing, the images are post-processed in a phase-resolved manner-binning all the images in each phase range (10 degrees each). Each image is tagged with its own phase information, then afterwards moved to the bin corresponding to the tag. Images in each bin are read in and converted to mathematical variables to calculate averages and standard deviations. Some selected data are presented here.

A sample acetone –PLIF image is shown in figure 5 (one of 900 similar images in this data set). It is assumed that the intensity or the brightness of each pixel is linearly proportional to the local fuel concentration ([14] showed that this induces up to 5% error, mainly due to CCD non-linearity). As is visible in the image in figure 5, the bright core part is denser with fuel, surrounded by less dense mixing regions, with pure air on the outside.

To compare these images to previous data, unmixedness needs to be defined for image data. Here, unmixedness is defined as:

$$U = \frac{\sigma^2}{(x_{\max} - < x >) \cdot (< x > - x_{\min})}, \qquad (1)$$

where σ is the standard deviation of fuel concentration at one pixel, x, fuel concentration, and <>, the average at the pixel. However, this measure of unmixedness can either be an indication of how unstable the fuel/air mixing is at a point or that the fuel concentration values are high.

Figure 5. Acetone PLIF image (16-bit Tiff), reduced to 225 x 300 pixels to highlight the laser – sheet region.

Some of the high unmixedness values (figure 6, equation (1)) are, as expected, located in the center fuel core region. To either side of the core, relatively low unmixedness is seen, implying that fuel and air in this region experience stable mixing. Outside of that region, there occur high unmixedness values, likely indicating unstable mixing rather than high fuel concentration. The boundary area has low unmixedness values since it is mostly pure air.

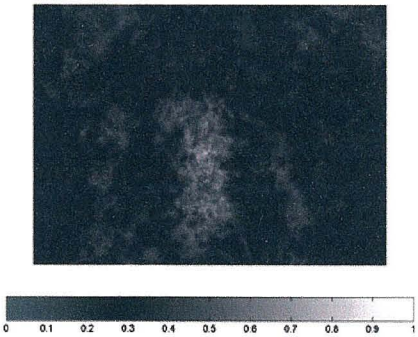

Figure 6. 2-D map of Unmixedness factor (37Hz, 60~70 degree phase, by equation (1))

Another way of defining unmixed ness is as follows.

$$U = \frac{\sigma^2}{(1 - < x >) \cdot < x >} , \qquad (2)$$

where σ is the standard deviation and <x> average of fuel concentration over the entire 2-D image, instead of one point with many measurements. A 2-D image collapses to a point value by this definition, and this is very useful when the phase resolved behavior of mixing rate over a period of time.

It has been shown by Fernandez et al. [6] that high values of unmixedness occur in the shear mixing layer of the flow (30-60% from the center, see figure 7). There is not much variation between cases with different excitation frequencies, but they show clear position dependency.

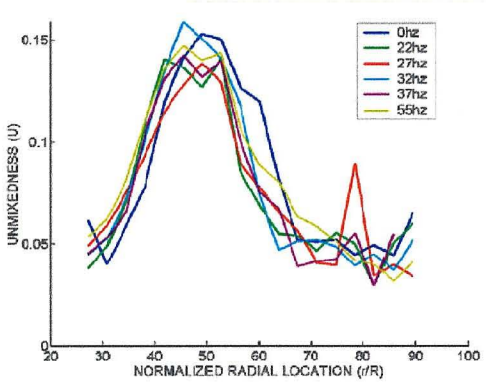

Figure 7. Temporal Unmixedness factor [6] at the neck of the eductor block by equation (1)

Further downstream from the eductor block, it seems the shear mixing zone seems to have moved and widened to 30 – 80 % region. The basic structure of the unmixedness distribution seems only to have been smeared (as is expected for a mixing process). The seemingly higher values of unmixedness factor downstream (fig 8) compared to those upstream values (fig. 7) does not necessarily mean more unsteady behavior of fuel/air mixture downstream, but, rather, the difference of the measurement techniques and their resolutions. In the core region close to the center, the variation is very small as expected from previous results. This shows the core region is still fuel dominant and needs further mixing. Qualitatively speaking, it seems that while the fuel/air mixing keeps the same structure downstream, the curves are less stiff; meaning the degree of instability in fuel/air mixing is decreasing downstream. Currently it is not possible to make any quantitative comparison since there is as yet no numerical correlation between the infrared absorption and the acetone-PLIF measurements.

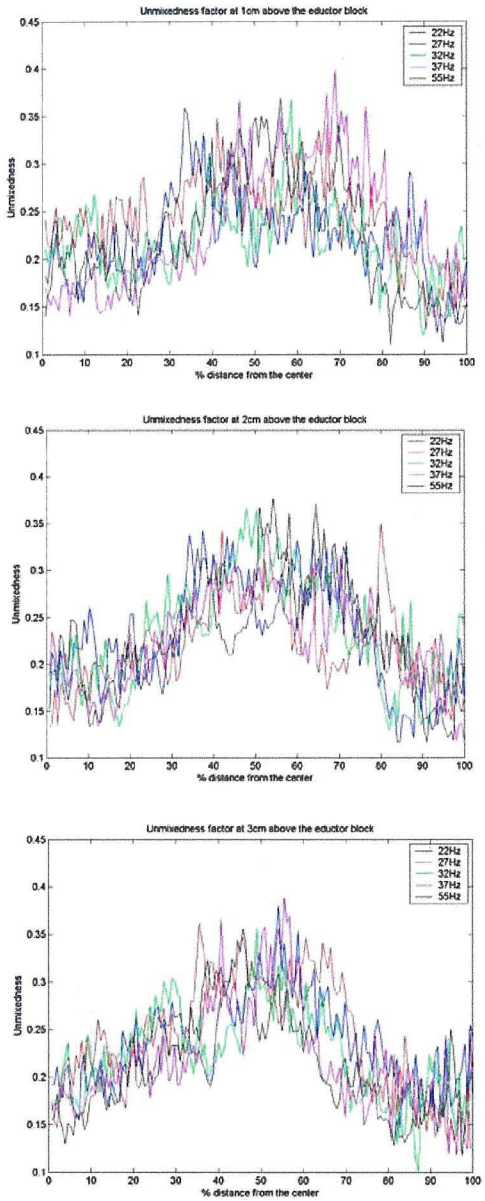

Figure 8. Temporal Unmixedness factor inside the mixing region with elevations (a) 1 cm, (b) 2 cm, and (c) 3 cm above the eductor block by equation (1).

Figure 9 shows the comparison of unmixedness factors at three different distances from the eductor block (1, 2, 3 cm each) at 37 Hz. As the flow goes down stream, it is shown that better and more stable mixing –smaller unmixedness-occurs in the outer region of 60-80% locations.

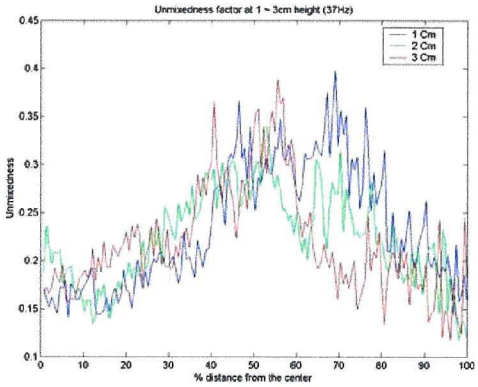

Figure 9. Temporal Unmixedness factors at each location with excitation frequency at 37 Hz

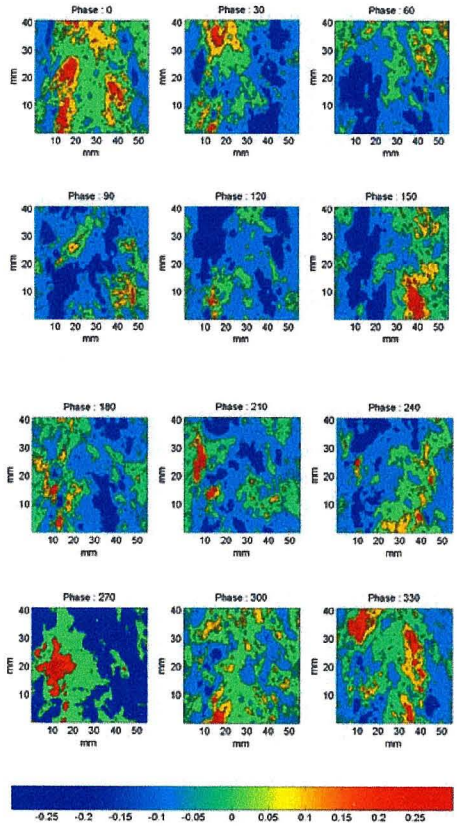

Figure 10. Distribution of fuel concentration by phase at 37 Hz. Contours show the difference from the average fuel distribution, normalized by the average value at that point.

Phase dependence of the mixing behavior is shown in figure 10. Here higher valued contours indicate higher than average fuel concentration for that region (reds and yellows), while the low value contours indicate lower than the average fuel concentration (dark and light blue). Each axis is presented in pixel, and the domain size is 55 x 42 mm. All the contours are scaled to values from -0.3 to 0.3. The phase is that of excitation pressure wave. For 37 Hz, the highest overall fuel concentration occurs at the pressure node (0, 180 degree), then decreases subsequently through 30(210) and 60(240) degrees until the pressure anti-nodes (90, 270 degree), and so on. The phase lead is approximately 90 degrees in this case. In the latter part of the phase, the fluctuation seems a little bit smeared by a possible secondary mode which is hard to see clearly at present phase resolution (10 degrees). The phase lead or lag is different for each frequency. The magnitude of the variation will be determined by evaluating the global unmixedness defined by equation (2).

Conclusion

As expected, the acetone-PLIF produced result, with a very low signal-to-noise ratio where only minimal adjustment was required for post-processing. So far, only qualitative comparisons have been performed.

The unmixedness defined by equation (1), a measure of variation in fuel/air mixing, showed the same structural shape downstream of eductor block as in the upstream region, and it was observed that as the flow progresses downstream, more mixing reduces the variation in the level of mixing. The same tendency was found at all frequencies investigated, showing that the impact on the mixing is not a frequency resonant effect.

From the behavior of fuel concentration, it can be concluded that the oscillations occurring inside the mixing region are closely related to the previously reported flame oscillation behavior [4, 5]. The phase lead and lag are very important in determining the response of fuel/air mixing due to the effects of acoustic forcing, and analysis will continue in an effort to extract a measured response (transfer) function of the mixing region.

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